

Transitioning Unmanned Ground Vehicle Research Technologies

E. Biagtan Pacis,^a H.R. Everett,^a N. Farrington,^a G. Kogut,^a B. Sights,^a T. Kramer^a
M. Thompson,^b D. Bruemmer,^c D. Few^c

^aSpace and Naval Warfare Systems Center, San Diego

^bThe Naval Undersea Warfare Center

^cIdaho National Laboratory

ABSTRACT

The Technology Transfer project employs a spiral development process to enhance the functionality and autonomy of mobile systems in the Joint Robotics Program (JRP) Robotic Systems Pool (RSP). The approach is to harvest prior and on-going developments that address the technology needs identified by emergent in-theatre requirements and users of the RSP. The component technologies are evaluated on a transition platform to identify the best features of the different approaches, which are then integrated and optimized to work in harmony in a complete solution. The result is an enabling mechanism that continuously capitalizes on state-of-the-art results from the research environment to create a standardized solution that can be easily transitioned to ongoing development programs. This paper focuses on particular research areas, specifically collision avoidance, simultaneous localization and mapping (SLAM), and target-following, and describes the results of their combined integration and optimization over the past 12 months.

Keywords: robotics, autonomy, collision avoidance, vision-tracking, SLAM, augmented virtuality, technology transfer.

1. BACKGROUND

The objective is to enhance the functionality and autonomy of mobile robotic systems in the Joint Robotics Program (JRP) Robotic Systems Pool through a spiral-development process that harvests existing component technologies for optimization. The Tactical Mobile Robot (TMR) program, sponsored by the Defense Advanced Research Projects Agency (DARPA), was transferred to Space and Naval Warfare Systems Center, San Diego (SSC San Diego) at the end of FY-02 to facilitate the transition of TMR-funded technology into ongoing JRP development efforts. SSC San Diego worked with a variety of DARPA contractors to extract relevant aspects of their research and port it to ongoing projects and systems associated with the JRP Robotic Systems Pool. The continuing search for supporting technologies has naturally expanded to other government research activities, academia, and industry to further foster emergent technology-transfer opportunities (Figure 1).

Accordingly, the JRP Technology Transfer Program has teamed with a number of organizations with similar ambitions, such as the Idaho National Laboratory (INL), to assist in the coordinated development, evaluation, and sharing of robotics technology. INL has a direct interest in autonomous robots for use in a variety of DOE missions, including homeland defense and critical infrastructure protection. This synergistic teaming between SSC San Diego and INL has two obvious advantages: 1) The INL Robotics Group, with similar objectives and experience, substantially augments the available manpower resources, allowing more technology options to be evaluated; and, 2) active DOE involvement opens up another major conduit for exporting the results into relevant government applications.

An equally important objective of the program is to also transition relevant technology enhancements into the private sector, in order to enhance the supporting industrial base. The National Center for Defense Robotics (NCDR) intends to enter into one or more CRADA agreements with SSC San Diego and INL (and possibly other government laboratories) to facilitate licensing on behalf of companies and other commercial entities belonging to the NCDR's Agile Robotics Alliance. Alliance companies are in turn expected to adapt, further develop, and integrate such technologies into current and planned unmanned systems they are engineering and producing for the military, as well as their targeted commercial markets. The NCDR expects to provide funding on a case-by-case basis to partner Alliance members with the appropriate government laboratories and to help cover the up-front assessment costs and/or further integration work that may be required.

1.1 Technical Challenges

In reexamining Figure 1, it seems readily apparent that each of the identified players is making a synergistic contribution to the collective whole, which in turn should be rather impressive indeed in terms of autonomous functionality once all the individual pieces come together. In reality, however, making it all work in harmony is a challenging task. The various developers each have their own preferences and constraints in terms of computer architectures, operating systems, languages, data formats, sensors, embedded hardware, and even power sources. In order to optimize the various component technologies into a single system, the sensors and computational hardware to support the software algorithms must first be integrated onto a common platform.

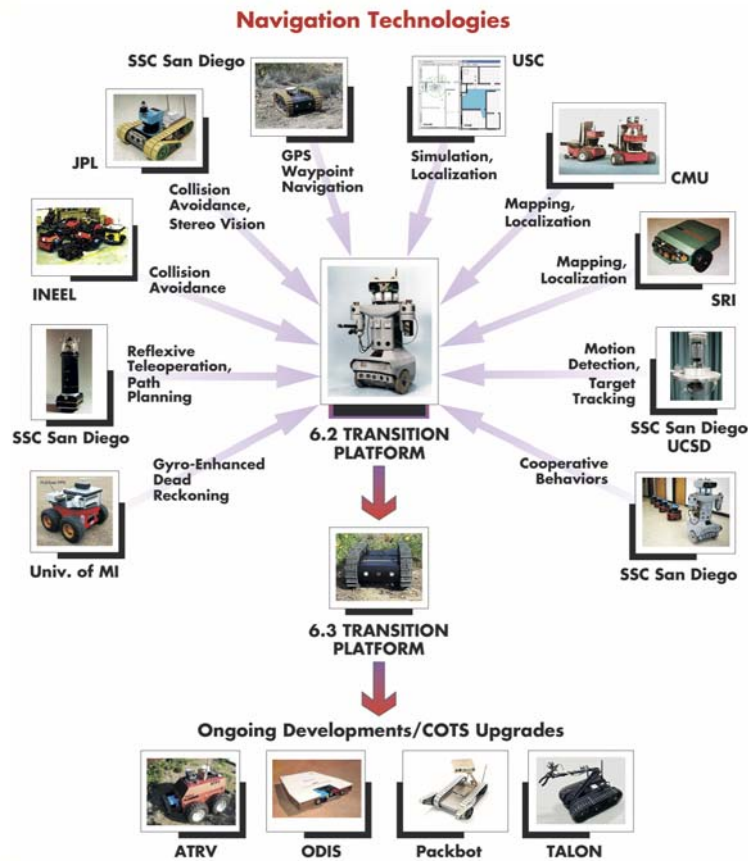


Figure 1. The Technology Transfer Program’s technical approach is to integrate, test, and optimize existing component technologies into a single solution on an evaluation platform, miniaturize for man-portable systems, and port to COTS platforms.

Problems arise when attempting to transition directly to man-portable-size (i.e., less than 80 pounds) systems in two main areas: 1) available power to support the required sensors and their associated processors, and, 2) the physical size of this additional hardware, particularly the sensors. Conventional batteries on current man-portable systems last only about 4 hours, and these rather simplistic teleoperated systems are nowhere near as complex or power hungry in comparison. For example, the run-time for an iRobot *PackBot* equipped with JPL’s stereo- and laser-based obstacle-avoidance systems developed under the TMR Program dropped from 4 hours to a mere 20 minutes (Figure 2). The SICK laser rangefinder draws 20 watts by itself, and its considerable size and weight (10 pounds) seriously hinders platform mobility, such as the ability to climb stairs. Accordingly, a strong need exists to provide a small, light-weight, non-contact scanning range sensor, optimized for the size/weight/power restrictions of man-



Figure 2. JPL’s *PackBot* equipped with TMR-era stereo and laser collision-avoidance sensors.

portable robots. Current state-of-the art (i.e., the SICK ladar) is typically geared towards automated guided vehicles used in factory automation, and as a result is far too heavy and power-hungry for use on small tactical robots.

Our approach for technology infusion to the man-portable systems of the JRP Robotic Systems Pool is therefore a three-step process: 1) integrate and optimize the component technologies to work in harmony, 2) scale the solution down in terms of power, size, and weight; and, 3) infuse the results into commercial-off-the-shelf systems. Numerous robotic test/evaluation platforms are employed at both SSC San Diego and INL to support this process.

1.2 Test/Evaluation Platforms

The original test and evaluation platform was *ROBART III* (Figure 3), which had the required size, a 90-amp-hour battery, readily available source code, and extensive diagnostics needed to host numerous sensors for navigation and intruder detection. It is currently equipped with a SICK scanning laser rangefinder, Sharp triangulation ranging sensors, passive-infrared (PIR) motion sensors, Polaroid ultrasonic rangefinders, a gyro-stabilized magnetic compass, and a fiber-optic rate gyro. *ROBART III*'s vision system includes a Visual Stone 360-degree omnidirectional camera and a Canon pan-tilt-zoom (PTZ) camera. With the reserve capacity to host even more sensors and their associated computational hardware, *ROBART III* serves as an optimal laboratory development platform for step one, integration and optimization of the various candidate software algorithms under consideration. It also has a non-lethal Gatling-style weapon (on right shoulder pod) to support higher-level behavior development in conjunction with the *Warfighter's Associate Concept*.¹

An iRobot *ATRV Senior* was similarly used at SSC San Diego in FY-04 to support outdoor navigation testing, the initial thought being *ROBART III* would address only indoor scenarios. With the introduction of the *Warfighter's Associate Concept* in FY-05, the distinction between indoor and outdoor platforms was dropped, since soldiers must routinely perform in both environments, and any robot intended to work alongside them as part of a synergistic team must do

likewise. Consequently, the *ATRV Senior* now serves as the primary evaluation platform for indoor localization algorithms because of its incredibly inaccurate dead-reckoning solution, which arises from its wide tires and skid-steer steering. Its larger size also provides the surface space and convenient mounting bars to install additional payloads, especially those of significant weight. For example, an *ATRV Senior* was loaned to the Applied Research Laboratory at the University of Texas (UT) at Austin for further testing of their human-presence sensor on a moving platform (further discussed in section 2.1.4). Another *ATRV Senior* is also on loan to UT's Robotics Research Group to support mobile manipulation development for vision-based control of a Barrett arm and Barrett hand.



Figure 3. *ROBART III*.



Figure 4. *URBOT* developed under MPRS Program.

Once the appropriate component technologies have been suitably integrated and tested on *ROBART III* and/or the *ATRV Senior*, the proven autonomy/functionality upgrade is ported over to the Man Portable Robotic System (MPRS) project at SSC San Diego for miniaturization on the *URBOT* (Figure 4), originally developed for use by the Army engineers for tunnel, sewer, cave, and urban structure reconnaissance. A GPS waypoint navigation capability was developed for the *URBOT* in 2002 and is currently being integrated with stereo-based collision avoidance technologies originally developed by the Jet Propulsion Lab under TMR.²

INL also has a pool of various iRobot and ActiveMedia platforms that have been used to optimize their *Advanced Robotic Control Architecture* (further discussed in Section 2.2) for cross-platform compatibility.

2. PROJECT STATUS UPDATE

Recent and ongoing military actions in Afghanistan and Iraq marked the first time robotic systems have played a meaningful role during actual combat operations. It is interesting to note that of the over 200 mobile robotic systems deployed, all of them are strictly tele-operated with no autonomous functionality. As a consequence, these systems appear organically attractive only in life-threatening scenarios, such as detection of chemical/biological/radiation hazards, mines, or improvised explosive devices. A need exists for significant improvements in both functionality (i.e., perform more useful tasks) and autonomy (i.e., with less human intervention) to increase the level of general acceptance and, hence, the number of units deployed by the user. The Technology Transfer Program has already produced phenomenal results addressing both these issues through optimization of component technologies integrated in FY-03 and FY-04.³ The following subsection describes our current status to develop a more complete solution that can significantly enhance warfighting capabilities.

2.1 Enhanced Functionalities and Autonomy

Improved autonomous navigation, including collision avoidance, mapping, localization, and path planning, was the primary focus through FY-04, and a system incorporating all of these functionalities has been optimized, as discussed in the subsections below.

2.1.1 Simultaneous Localization and Mapping

The Consistent Pose Estimation (CPE) mapping technology was developed at Stanford Research Institute International (SRI). CPE efficiently incorporates new laser scan information into a growing map and also addresses the challenging problem of *loop closure*, how to optimally register laser information when the robot returns to an area previously explored. CPE is one method of performing Simultaneous Localization and Mapping (*SLAM*), based on original work by Lu and Milios,⁴ who showed that information from the robot's encoders and laser sensors could be represented as a network of probabilistic constraints linking the successive poses of the robot.

SRI has implemented and further developed localization algorithms using a representation of the robot's state space based on Monte Carlo sampling.⁵ Introduced in 1970,⁶ Monte Carlo Localization (MCL) methods have more recently been applied with good results in the fields of target tracking, computer vision, and robot localization^{5, 7}. The Monte Carlo technique inherits the benefits of previously introduced Markovian probability-grid approaches for position estimation⁸ and provides an extremely efficient technique for mobile robot localization. One bottleneck in the MCL algorithm is the necessity for checking the posterior probability of each sample against the map, based on the current laser readings. SRI has developed an efficient method for performing this computation, using a correlation technique derived from computer vision algorithms.⁹

Follow-on plans are to integrate and evaluate multi-robot mapping techniques developed under DARPA's Software for Distributed Robotics (SDR) Program.¹⁰

2.1.2 Collision Avoidance

SRI's SLAM algorithms were integrated with collision-avoidance techniques developed by INL specifically for use in dynamic unknown environments. The collision-avoidance algorithms take a behavior-based approach that emphasizes a tight coupling between sensing and action, with each of the sensors contributing to an array of robot-centric regions to which the robot responds, based on fuzzy-logic rules that control its translational and rotational velocities. These rules not only apply to each individual region, but can be triggered by combinations and patterns found within the array of regions. In implementing this scheme INL uses a subsumption architecture similar to that employed on ROBART I,¹¹ wherein atomistic behaviors such as collision avoidance run in parallel with, but can be subsumed by, other reactive behaviors, such as "maneuver-around" and "get unstuck." Collision avoidance is a bottom-layer behavior, and although it underlies many different reactive and deliberative capabilities, it runs independently.

INL has also incorporated other deliberative behaviors that function at a level above the reactive behaviors. Once the reactive behaviors are "satisfied," the deliberative behaviors may take control, allowing the robot to exploit the map in order to support behaviors such as *area search*, *patrol perimeter*, and *follow route*. INL's *guarded motion* (i.e., reflexive teleoperation) capabilities employ several different sensors (i.e., scanning laser, infrared triangulation, sonar, tactile, inertial, and tilt), fusing available perceptual data into regions that represent the ability of the robot to move safely in a given direction. The algorithm also continuously calculates an *event horizon* representing the last possible moment for

the collision-avoidance behavior to successfully intervene upon goal-based behaviors at the current speed. By calculating this *event horizon* many times each second, the robot can smoothly scale down its velocity as a function of congestion without necessarily fully impeding motion. When a full stop is required, use of the *event horizon* ensures that the robot comes to a halt at the same distance from an obstacle regardless of its initial velocity.

2.1.3 Global Path Planner

In early FY-05, SRI added a stand-alone global path planner that operates upon the map generated by the SLAM algorithm. This gradient-based planner uses the occupancy grid as the planning environment and generates an optimal path from the robot's current position to any desired destination within the map. An example path trajectory is shown in Figure 5.

The global path planner is also integrated with the local path planner, allowing the robot to maneuver from a known environment (area that has been previously explored and mapped) to an unknown environment (area that is not yet mapped), maximizing both efficiency and robustness. For example, when a destination goal sent to the robot is located outside the current map, the global path planner will plan a path to that point in the map closest to the destination, and then the local path planner will seamlessly guide the robot in the unknown environment.

2.1.4 Motion Detection on the Move

Performing intruder detection from a moving platform is a difficult problem compared to sensing intruders with a static sensor, where all that is required is to detect a change in sensor output. An intruder must be moving to enter the field-of-view of a fixed sensor, hence motion detection works very well. Detecting a human from a moving platform is considerably more challenging because the background is continuously changing, and averaging or background subtraction alone will be unreliable by itself. Furthermore, the intruder may not always be moving.

SRI's SLAM technology was leveraged to develop a change-detection-on-the-move capability. Once a map is built representing the monitored area, the robot uses the occupancy grid from the SLAM algorithm to detect changes within the environment. The location of the change is sent as a vector to a video camera which then displays the "intruder" to the operator. This technology is being leveraged by DTRA-funded efforts to demonstrate human presence detection and assessment (HPDA) from a moving robotic platform. Using the laser-based SLAM technology will allow the robot to receive range information to objects in its environment and determine when an object is "new," meaning it had not previously been detected. The output vector from the change-detection algorithm will cue a passive microwave sensor being developed by the Applied Research Laboratory at the University of Texas, Austin that detects signatures unique to humans for further assessment.

2.1.5 Vision-Based Target Identification/Following

The same concept of using a vector from a sensor payload to cue an assessment reaction is employed by the target-following behavior. The Sony PTZ Camera onboard the *ATRV Senior* already includes color-blob tracking and edge-detection software. The camera easily tracks a pre-taught object, continuously outputting the target's relative bearing to the drive subsystem, enabling the robot to track and follow a pre-taught target while avoiding obstacles. A person-following routine for the Segway Remote Mobility Platform (RMP) was also developed at SSC San Diego, allowing the RMP to continuously follow a person in the same manner. The system developed for the Segway RMP, however, uses hue-tracking methods that are more independent of varying lighting conditions than color-blob tracking. The system also allows for gradual changes in the appearance of the tracked target, sometimes due to the dramatically differing characteristics of sunlight versus fluorescent light when the robot is moving from an indoor to outdoor environment.

Distributed Interactive Video Array (DIVA) technology originally developed at UCSD's Computer Vision and Robotics Research (CVRR) Laboratory has been ported over to *ROBART III* in FY-04 to provide an advanced vision capability for the robot, as well as a research tool to develop and investigate additional vision-tracking algorithms. For example,

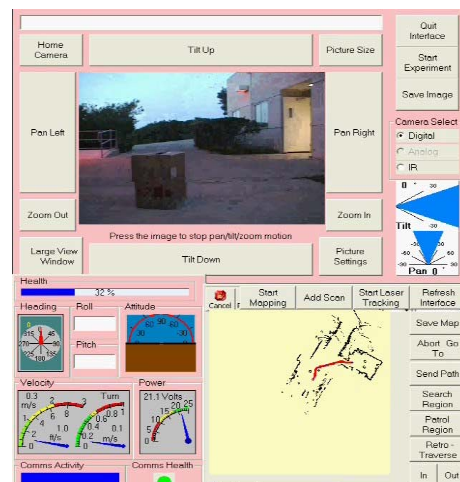


Figure 5. Path trajectory (red line in bottom map display) planned by the global path planner to reenter the building through the door visible in the right top corner of the video feedback.

ROBART III currently maintains a pre-taught database of digital color pictures of potential targets and their associated “vulnerabilities.” The vision system compares these target templates with live images from its incoming video stream. *ROBART III* then performs a two-stage *search-and-engage* algorithm,¹ wherein the vision system first performs a wide-area scan for a pre-taught class of objects, then cues the PTZ camera to zoom in and search for specific “vulnerabilities” associated with that particular target. The non-lethal weapon is automatically trained accordingly with the aid of a bore-sighted targeting laser, and then fired under operator supervision, using a color-correlation-matching algorithm (see Figure 6).

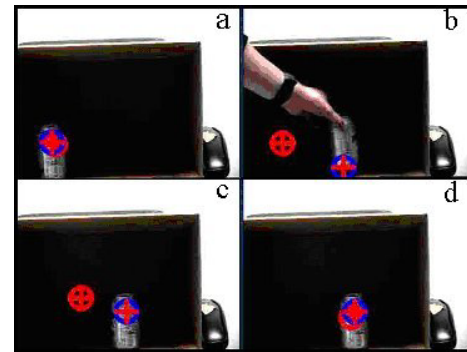


Figure 6. a) Vision System and targeting laser on detected vulnerability (soda can); b) Can is relocated and tracked in real-time; c) Targeting laser servos to new location; d) Laser now relocated on new target position, ready to fire weapon.

Future plans are to extend the person-following routine developed on the Segway RMP by fusing data from visual and IR cameras. Fusing color data with a human's IR-signature should avoid tracking errors caused by a similarly-colored background or people wearing similar clothing. INL and SSC San Diego are also collaborating on a system to detect and model doors, doorknobs, and name placards for robots navigating office environments. This capability will first be used to assist the robot in locating individual offices and later assist in grasping and manipulating doorknobs or opening doors.

2.2 Common Architecture

To facilitate integration and ultimate transfer to ongoing programs, our approach is to adapt and standardize on a reconfigurable software framework that can be easily ported from one robotic system to another. Real progress will not be made in robotics until there are mutually agreeable standards for combining different component technologies. The huge success of the Internet, for instance, was only made possible with mutually agreed upon standards such as the TCP/IP protocol.

There are many reasons why robotic standardization has not happened sooner, the principle factor being there is not yet financial motivation for such standards. Early computer makers in the 1950s and 60s did not standardize their products because of the fear of competition and a minimal number of computer users. The transition of information technology from an engineering solution to a commodity eventually precipitated the need for standardization. As the number of users grew, interoperability between different computer products became more critical. Another major reason that standardization has not readily taken hold is that there are varying approaches to developing autonomous robotic technologies, particularly with regard to behavior arbitration, knowledge representation, and machine learning.

In an attempt to develop cross-platform compatibility, a few de facto standards have more recently emerged for lower-level robotic control. Many of these are commercial software packages, such as ActivMedia's *ARIA* and iRobot's *Mobility* and *Aware*. There are also some open-source software standards such as the University of Southern California's *Player/Stage* project, Université de Sherbrooke's *MARIE*, and Carnegie Mellon University's *CARMEN*, all of which address the lowest levels of robotic control. They attempt to provide an abstract interface to the physical hardware and can also be used to provide interfaces to robotic algorithms.

One of the most promising open-source efforts for standardization of low-level control we have investigated is the University of Southern California *Player/Stage* project. The goal of the *Player* server is to provide a TCP/IP or UDP/IP network interface for robotic sensors and actuators. The project's mailing list currently has hundreds of subscribers, and the software has been downloaded thousands of times. Even though the software has no commercial support, the active developer community makes it easy to fix bugs. And while the software is not perfect, it does a very good job for its intended purpose.

One primary advantage to adopting *Player* approach is that it is fully extendable, making it very easy to add support for new hardware, and users have already contributed many different drivers for the most popular robotic hardware, peripherals, sensors, etc. (There are currently 63 drivers integrated into the distribution, not including custom drivers that users have not published.) The usefulness of the *Player* software increases almost exponentially with the number of

drivers available, as weeks worth of programming can be saved by using an existing driver for one's hardware. Under the Technology Transfer effort, *Player* drivers were created for *ROBART III*'s custom sensors and actuators, including a differential drive controller, sonar rangefinders, a power system interface, a speech synthesizer, and a non-lethal weapon. Some improvements were contributed back to the *Player* project, such as modifications to the Canon *VC-C4R* driver.

Despite the aforementioned benefits of using *Player*, there are some disadvantages. We have encountered bugs and non-robust driver code while developing software with *Player*, which were resolved by manually debugging the software and then contributing trouble reports to the development community. At this time, many developers still consider *Player* to be experimental, as further development is needed for robust performance on fielded platforms.

Using *Player* as the low-level interface allows a logical separation of high-level behaviors and low-level control. For example, INL's Advanced Robotic Control Architecture has been optimized to be independent of low-level control. The Intelligence Kernel implements a class library for robotic platforms, sensors, and actuators, allowing any type of low-level interface to be used. INL's control architecture currently supports *Player*, *Mobility*, *ARIA*, and some other proprietary interfaces. (See Figure 7.)

INL's control architecture is also independent of the robot's geometry and sensor suite.¹² The entire framework is object oriented, allowing all software, including all behaviors and associated autonomous control, to be easily ported to a variety of robotic platforms by editing a parameters list (i.e., for robot length, width, maximum speed). Moreover, the system allows the robot to recognize what sensors it has available at any given time and adjust its behavior accordingly. Such a control architecture is ideal for the Technology Transfer Program, as it allows easy porting and testing of advanced behavior functionalities on multiple platforms.

Another notable standardization effort is the Joint Architecture for Unmanned Systems (JAUS), a JRP initiative to define and implement an upper-level architecture design for a common interface to a variety of unmanned vehicles, sensors, and munitions.¹³ JAUS is component-based, specifying data formats and methods of communication among computing nodes. The JAUS Working Group (made up of members from the U.S. government, industry and academia) defines methods for message passing and standards for component behaviors in order to be independent of technology, computer hardware, operator use, vehicle platform, and mission. SSC San Diego is an active member of the Working Group and has developed a JAUS interface for INL's Robotic Control Architecture so that any JAUS-compliant Operator Control Unit (OCU) can control any robot using the INL onboard architecture.

2.3 Augmented Virtuality

Controlling or supervising advanced robotic behaviors requires a suitable high-level interface human-robot for mixed-initiative control and efficient tasking. In an attempt to develop a shared workspace for effective command and control, an *augmented virtuality* interface, based on underlying technologies developed at Brigham Young University,¹⁴ is being developed that can link additional sensor information to the robot's world model.



Figure 7. The INL control architecture has been ported to their pool of various iRobot and ActiveMedia platforms shown above.

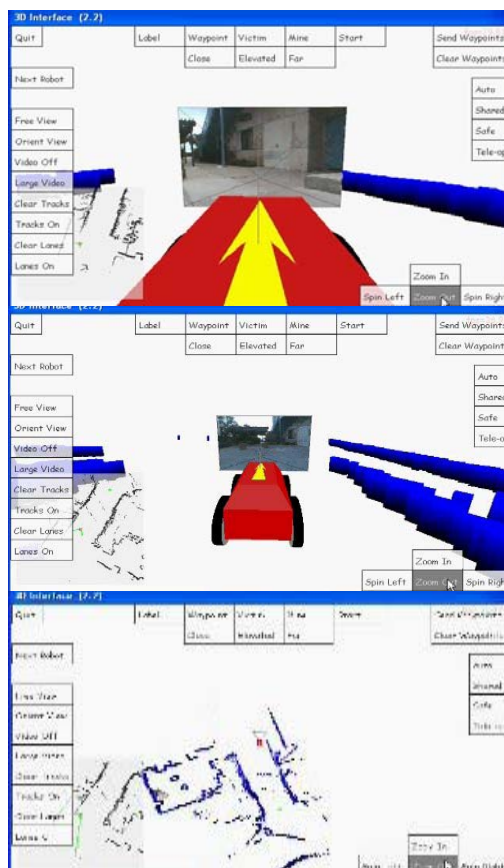


Figure 8. The operator's perspective of the environment is adjustable by changing the zoom, pitch, and yaw of the 2 1/2-D interface.

The world representation is not true 3-D, but obtained by arbitrarily growing the laser-generated 2-D SLAM map some finite vertical distance, and consequently referred to as 2½-D. The zoom, pitch, and yaw of the 2½-D interface can be changed, allowing the operator's perspective to transition from a bird's-eye view, where the entire environment can be seen at once, to a first-person perspective (Figure 8). This approach has been shown to provide improved situational awareness for driving the robot and understanding the local environment (especially in tight spaces) than actual real-time video imagery.¹⁵ The *augmented virtuality* interface can also be supported with a low-bandwidth data link (e.g., 900-MHz serial RF link at 9600 baud), facilitating communication through thick concrete and rebar in urban environments (see Figure 9).

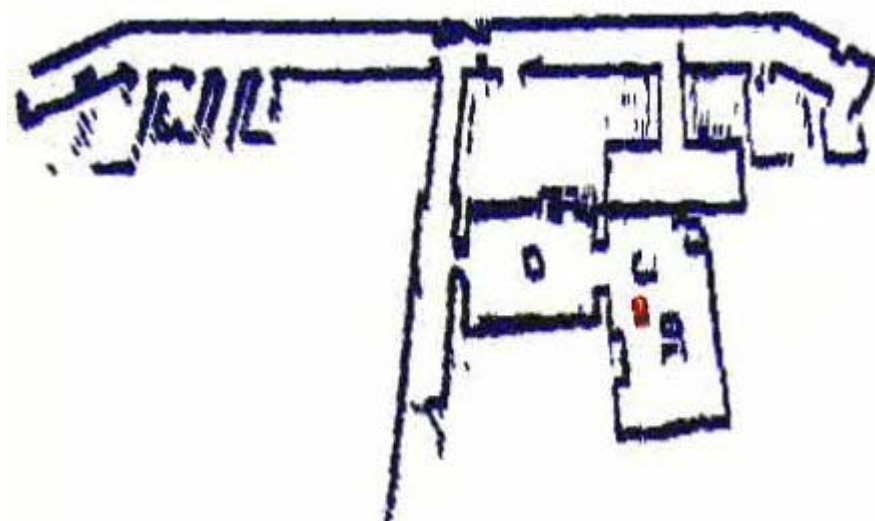


Figure 9. 2½-D interface obtained from the 2-D SLAM map of Battery Woodward, an underground World War II bunker at SSC San Diego built with thick concrete walls.

We “augment” the 2½-D interface with even more virtual information derived from on-board sensor readings and/or operator input. For example, alarm readings from the CHARS (chemical, gas, radiological sensor) application payload developed at SSC San Diego,¹⁶ could be “tagged” with an appropriate icon in the *augmented-virtuality* layer of the SLAM world model. Likewise, the robot's vision camera can be treated as another onboard sensor that can contribute snippets of video and/or still imagery (see Figure 10 [better picture]) of conditions encountered at specific locations, which similarly be linked to this same tag, providing both virtual and real elements for later viewing. Any data from onboard sensors can be time- and position-stamped with respect to the virtual model, making registration (at least of robot-collected data) rather simplistic.

Future plans are to integrate the *augmented virtuality* interface with a geographic information system (GIS) system, in order to further support the need to bring all sources of data together in a map-like environment to be visually plotted and analyzed. Such a tool can be used in multiple DOD and DOE domains, such as security, force protection, intelligence, command and control, peacekeeping operations, and facilities management.

As a result of widespread adoption of global-positioning-system (GPS) technology, remote sensing, and surveying, the availability of spatial data is growing fast. Furthermore, advancing spatial technology makes it possible to store and manage all of this data in a standardized database management system (DBMS). An inherent advantage of this approach is the ability to augment existing published geo-spatial data such as aerial

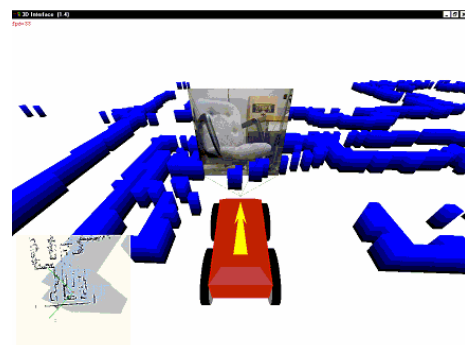


Figure 10. Screenshot of the virtual model fused with real-time video images from an ATRV exploring INL office space.

photos, vector maps, and terrain elevation data to meet the needs of a specific mission. For example, a SLAM-equipped robot could autonomously map out an unknown bunker, and then upload the 2-D (or even 2½-D) model of the bunker to a GIS database. Once the data is imported into the GIS system, it can be seamlessly viewed with other data sources, as well as analyzed using other GIS applications. The highest resolution elevation data commonly available is Digital Terrain Elevation Data (DTED) Level 2, which provides 30-meter resolution. Using differential GPS, an unmanned vehicle could explore an area and develop extremely high-resolution elevation data that could be used for line-of-sight calculations, radio coverage analysis, or other applications.

SSC San Diego has been approved to use the Commercial Joint Mapping Toolkit (C/JMTK). C/JMTK is a major acquisition program contracted to TASC, a business unit of Northrop Grumman Information Technology (IT) by the National Imagery and Mapping Agency (NIMA) to provide a comprehensive standardized commercial toolkit of software components for the capture, management, dissemination, analysis and visualization of geographic and related information for all DOD battle-space applications. C/JMTK is based on the Environmental Systems Research Institute (ESRI) family of software products called *ArcGIS*, which is built on a common architecture that forms a multi-user GIS. SSC San Diego is developing a 3-D command-and-control system based on the C/JMTK framework that will provide unprecedented visualization capabilities. By adopting the GIS model, this system will be able to easily share information with many other military command-and-control systems, such as the Global Command and Control System-Joint (GCCS-J).

C/JMTK includes ArcGIS software components to serve as the DBMS, Internet server, a Spatial Analyst, a 3D Analyst, and a Military Overlay Editor (MOLE). As unknown interior structures are explored and mapped, their corresponding *augmented virtuality* interfaces can be added to the DBMS and made available over the Internet. With the 3-D Analyst, the tools for providing 3-D visualization and analysis are present to incorporate the 2 ½-D augmented virtual representation of the interior structures. The Military Overlay Editor (MOLE) is a symbol generator and editor to create and position unit symbols against a background of geographic data. The MOLE software component can be used to create new standardized symbols used to tag locations in the *augmented virtuality* interfaces of different data gathered from various sensor payloads.

3. PLANNED DEMONSTRATION

Future plans are to demonstrate the autonomous deployment and collaborative behaviors of multiple robots in a MOUT environment. The individual phases and supporting technology areas needed are already demonstratable at SSC San Diego as stand-alone systems, such as GPS waypoint navigation, deployment of marsupial robots, and mapping of interior structures. The planned FY-05 demonstration will illustrate the integration and further development of these stand-alone systems as follows.

An optimal path of approach is first created by the operator selecting a series of waypoints on the Multi-robot Operator Control Unit (MOCU) ¹⁷ map display, based on recently downloaded overhead imagery as shown in Figure 11. The delivery vehicle is then dispatched to the insertion point by executing

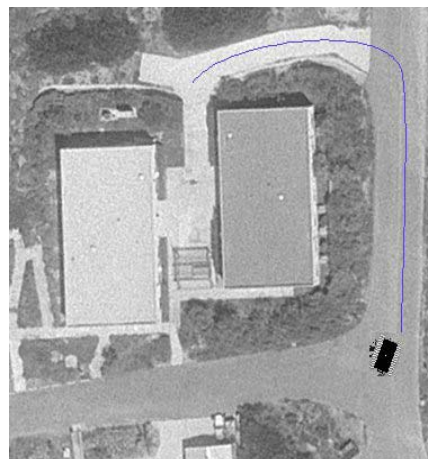


Figure 11. MOCU display showing planned route to insertion point for the marsupial-carrier configuration (Figure 12).



Figure 12. MDARS-Expeditionary robotic vehicle is shown deploying an Urban Robot (URBOT) at the insertion point, in preparation for the building-penetration phase of the demo.



Figure 13. A special “information-available” icon appears on the MOCU display indicating the robot is uploading data for the associated interior structure (i.e., cave, bunker, building).

autonomous waypoint navigation and collision avoidance under remote operator supervision. This diesel-powered vehicle is equipped with a marsupial carrier for a battery-powered man-portable robot, such as the SSC San Diego *URBOT*, the Foster-Miller *Talon*, or the iRobot *Packbot*. Upon arrival at the insertion point, the tracked man-portable robot (in this case, an *URBOT* as shown in Figure 12) descends from the marsupial carrier and moves toward the building entrance. The delivery vehicle can remain on station as a communications relay, provide defensive cover, or be otherwise redeployed as desired by the operator.

The man-portable robot seamlessly transitions to SLAM navigational mode upon entering the building, as GPS will immediately cease to function due to satellite occlusion. In all probability, the RF link will also be lost as the robot penetrates deeper into the interior structure, but this does not represent a problem either, since maintaining a real-time data link is not required. The SLAM-enabled robot will continue to execute a complete search of the bunker in autonomous fashion, augmenting its evolving world model with appropriate sensor data, still imagery, and video clips as appropriate. If a valid communications path is available at any point, a copy of the *augmented virtuality* model is passed back to the operator control unit, whereupon an “information available” icon appears on the building being explored, as shown in Figure 13. Clicking on the icon will bring up the *augmented virtuality* display of the interior structure (Figure 14).



Figure 14. Clicking on the “information-available” icon for a so-designated structure brings up the augmented-virtuality display of the structure’s interior being mapped by the robot.

Upon completion of the structure sweep, the robot plans a path back to the entrance and exits the bunker, switching back to GPS navigation, and re-establishing RF communications if not already acquired. The robot can then be recovered by the marsupial carrier for recharging and subsequent redeployment, or instructed to search and map another nearby structure.

4. CONCLUSION

Military robotic capabilities are being rapidly expanded through the efforts of the Technology Transfer program managed by the Space and Naval Warfare Systems Center, San Diego. To address the need for advanced functionality and autonomy based on feedback from the JRP Robotics Systems Pool users, this program has combined the development efforts of many key players in the robotics community for transition to COTS systems. Efforts in FY-02 thru FY-05 have produced an optimized system for advanced navigation behaviors (including collision avoidance, mapping, localization, path planning, and target identification/tracking). on a cross-platform compatible software framework. An *augmented virtuality* interface is also being developed to combine the enhanced functionalities with a more intuitive and informative user interface, increasing the warfighter’s situational awareness and safety. The Technology Transfer program, thus, serves as enabling mechanism that continuously capitalizes on state-of-the-art contributions from the research environment to create a standardized solution that can be easily transitioned to ongoing development programs.

5. REFERENCES

1. Everett, H.R., Pacis, E.B., Kogut, G., Farrington, N., and S. Khurana, “Towards a Warfighter’s Associate: Eliminating the Operator Control Unit,” SPIE Proc. 5609: Mobile Robots XVII, Philadelphia, PA, October 26 – 28, 2004.
2. Bruch, M.H., Lum, J., Yee, S., Tran, N. “Advances in autonomy for small UGVs,” SPIE Proc. 5804: Unmanned Ground Vehicle Technology VII, Orlando, FL, March 29 – 31, 2005.
3. Pacis Estrellina, Everett H.R., “Enhancing Functionality and Autonomy in Man-Portable Robots,” Proceedings, SPIE Unmanned Ground Vehicle Technology VI, Defense and Security, Orlando, FL, 12-16 April, 2004.
4. Lu, F. and E.E. Milios, “Globally Consistent Range Scan Alignment for Environment Mapping,” *Autonomous Robots*, 4(4), 1997.

5. D. Fox, W. Burgard, F. Dellaert, and S. Thrun, "Monte Carlo Localization: Efficient Position Estimation for Mobile Robots," Sixteenth National Conference on Artificial Intelligence (AAAI'99), July, 1999.
6. J. Handschin. "Monte Carlo Techniques for prediction and filtering of non-linear stochastic processes." *Automatica* 6, 1970.
7. F. Dellaert, D. Fox, W. Burgard, and S. Thrun, "Monte Carlo Localization for Mobile Robots," IEEE International Conference on Robotics and Automation (ICRA99), May, 1999.
8. W. Burgard, D. Fox, D. Hennig, and T. Schmidt. "Estimating the absolute position of a mobile robot using position probability grids," Thirteenth National Conference on Artificial Intelligence, pp. 896-901, 1996.
9. Kurt Konolige, Ken Chou: Markov Localization using Correlation, *IJCAI 1999*: 1154-1159.
10. <http://www.darpa.mil/ipto/programs/sdr/>
11. Everett, H.R., *A Microprocessor Controlled Autonomous Sentry Robot*, Masters Thesis, Naval Postgraduate School, Monterey, CA, October, 1982.
12. D.J. Bruemmer, D.A. Few, M.C. Walton, R.L. Boring, J.L. Marble, C. Nielsen, and J. Garner. "Turn off the television!: Real-world robotic exploration experiments with a virtual 3-D display." To appear in Proceedings of the Hawaii International Conference on System Sciences (HICSS) 2005.
13. "Joint Architecture for Unmanned Systems," Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. <<http://www.jauswg.org/>>.
14. C.W. Nielsen, B. Ricks, M.A. Goodrich, D. Bruemmer, D. Few, and M. Walton. "Snapshots for Semantic Maps." Proceedings of 2004 IEEE Conference on Systems, Man, and Cybernetics. October 10-13, 2004, The Hague, The Netherlands.
15. D.J. Bruemmer, D.A. Few, R.L. Boring, J.L. Marble, M. Walton, and C. Nielsen. "Let Rover take over: A study of mixed-initiative control for remote robotic search and detection." IEEE Transactions on Systems, Man, and Cybernetics.
16. "CHARS Payload Deployed," Robotics Update Newsletter, SPAWAR Systems Center, San Diego, Code 2371, Unmanned Systems Branch, March 2004, Vol. 4, No.1
17. Bruch, M.H., Gilbreath, G.A., Muelhauser, J.W., and J.Q. Lum, "Accurate Waypoint Navigation Using Non-differential GPS," AUVSI Unmanned Systems 2002, Lake Buena Vista, FL, July 9-11, 2002.